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Laser Incising of Wood: A Review

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ABSTRACT

Preservative treatment is necessary to provide adequate service lives in products manufactured from low durability timbers. However, the low permeability of the heartwoods of many species leads to poor preservative uptake and penetration. To improve treatment, incising has been used to produce new flow paths. Laser incising is effective at improving flow of preservative into wood and is said to produce less mechanical damage and loss of strength than conventional mechanical incising. This review provides an overview of laser incision of woods, including the effects of laser types (wavelength and pulse duration) on incision rate, preservative treatability/retention in wood and structural changes to the wood. Best practices and further areas for development for laser incising of wood are also presented and discussed.

Keywords: Laser; Incision; Wood; Wavelength; Preservative; Treatability

1 INTRODUCTION

Around 2000 commercial wood species are used indoors for furniture, flooring, interior joinery, joists and roof trusses, or outdoors for exterior joinery, decking, fencing, pilings and lock gates. Timber products in service are exposed to different environmental conditions in one of five Use Classes, ranging from wood indoors where it is dry (UC1), to wood submerged in freshwater/seawater (UC5), where it is constantly wet [1,2]. The risk of attack by insects, fungi or other organisms differs with Use Class. Where non-durable timbers are used for applications, there is a high risk from decay. One such example is that of outdoor fence posts (UC4) and as a result, these are preservative treated [1,2] in order to maximize their product life.

Fungal decay requires wood to have a moisture content >23% and wood products exposed to long-term wetting are at a greater risk from decay. In ground contact, un-treated wood takes between 5-8 years to completely decay in a temperate climate [3,4], whereas the desired service life for a preservative treated fence post, for example, is 15-years. Decay is therefore prevented/slowed through the utilisation of preservative treatment [5]. The effectiveness of protection depends on preservative type, retention, level of fixation and distribution of the protective chemical agent within the piece. Penetration is measured inwards from the more difficult to treat lateral faces and is influenced by preservative, method of application and permeability of the wood.

Preservative flow rate is generally greatest along the grain [5]. Radial flow occurs more slowly with greatest flow normally via rays. Tangential flow is slowest, with fewest flow paths available in this direction. Permeability also varies between species, particularly between softwoods (conifers) and hardwoods (broadleaves). Most preservative treatments are performed on softwoods such as pines and spruces. Even between these species, differences in wood anatomy at a cellular level influence permeability [6,7]. Longitudinal flow of fluids is greater in pines than spruces, as a result of aspiration of bordered pits in the tracheids of the spruce earlywood [8,9]. Difficulties in achieving preservative penetration in some timbers has led to the use of incising techniques to produce artificial flow paths to improve treatability from lateral faces [10-16]. This has given rise to techniques which can ensure the enhanced flow of preservatives through the incised woods, improving the wood treatment manufacturing process.

Preservatives are applied using two techniques. Non-pressure techniques include dipping, soaking, brushing, and spraying [17], and usually give relatively low levels of preservative penetration and retention. They are used where moderate improvement of durability is required, or for preservatives which have good levels of diffusion into the wood, on standing, after treatment [18,19]. The effectiveness of non-pressure methods depends on the kind of wood, its moisture content (in the case of diffusion), method of application, duration of treatment and the preservative used [20]. Techniques such as dipping and diffusion, may take up to 48 hours to complete. The other techniques are that of pressure-based treatments [1,5]. Where a high preservative retention is required, pressure-based techniques end to be the optimal method. Pressure-based treatments take 1.5 to 5 hours to complete, with longer cycles typically used for difficult to treat (refractory) species. This increased rate of treatment is more economically viable [21]. The wood is placed in an autoclave to allow the preservative to be applied under pressures of up to 10.5 -16 bar, resulting in rapid penetration of the chemical into the timber [1]. The most commonly used process is the ‘empty cell’ process, where fluid is removed from cell lumen after treatment. The process uses a vacuum prior to impregnation to remove air from the wood. Preservative is then introduced to fill the autoclave and a pressure of 12 bar applied for 30-180 minutes to force preservative into voids in the wood structure. After the treatment, the liquid is drained, and a second vacuum applied to draw preservative out of the lumens, leaving the cell wall treated.

After treatment, the timber is stood to enable preservative fixation and evaporation of the carrier fluid. The treated zone (envelope) at the outside of the timber protects underlying timber from decay. The degree of protection depends on the type of preservative, retention and depth of penetration [20]. Deeper penetration is usually desirable since there is less chance of the treatment envelope being breached, exposing untreated wood beneath.

Ease of treatment (treatability) also varies within the tree stem, with the heartwood (towards the centre of the tree) being more closed to preservative treatment fluids than the sapwood [20]. This is either due to encrustation by extractive chemicals laid down by the tree during heartwood formation, or due to closure of the cellular structure. In softwoods, the closure may result from aspiration of bordered pits between tracheids, and in hardwoods formation of tyloses in the vessels [9,22]. Heartwood formation protects wood in the living tree against decay [23]. The Treatability of commercial timbers are reported in Standard EN350. Table 1 presents the classification of wood species based on their level of impregnability.

1.1 Permeability Improvement Using Pre-Treatment

In difficult to treat woods, different methods have been adopted to increase the permeability including incision (mechanical or laser), steaming, solvent-exchange drying, critical point drying and biological treatments [24]. Incision processes facilitate preservative uptake [24] and involve drilling or slitting the surface of the wood [25].

Mechanical incising ruptures wood cells at intervals along and across the piece using knives or pins, so that the timber is rendered sufficiently porous to permit the flow of liquids into the wood [26,27]. Laser incision allows holes (usually on the scale of μm) to be created in the wood either by ablation or vaporisation. Incision dimensions, incision pattern, and incision density have a strong effect not only on preservative uptake, but also on mechanical strength. The more effective the incision pattern at increasing preservative uptake, the lower the mechanical strength [10]. For example, mechanical incising of structural timber in the dry state led to a loss of up to 10% of the Modulus of Elasticity (MOE) and 15-25% loss of flexural strength (or Modulus of Rupture, MOR) in bending tests [10]. However, since incising is normally undertaken on wet wood, this may result in lower strength losses than for dry wood and highlights the importance of the initial state of the wood prior to incision.

The increased penetration and retention of preservative, because of incising, is shown in Table 2. Although mechanical incising improved preservative penetration it was not flexible and unable to produce complex patterns [11,28]. This has implications with the uptake of these mechanical incising technologies in industry as it limits the potential penetration of the liquid preservatives. Considering the literature, there is very little information available on the effects of laser incising on wood strength. This is in addition to little information being available in the literature in the terms of works relating to laser incising, in general. Having said that, it is considered, and believed by the Authors, that the strength of incised wood is likely to be dependent on the laser incision density, hole geometry, and specimen size as is the case for mechanical incising [10].

An additional effect of incising is the reduction of drying time resulting from increased permeability. Drying of timber following preservative treatment usually takes several days, but laser incising has been shown to reduce the drying time of wood by 7 - 70% [29,30].

2 LASER-MATERIAL INTERACTION IN LASER DRILLING

Laser drilling is a non-contact process, which provides flexibility, precision, and reproducibility, to drill quality holes with a high aspect ratio (the ratio of the hole's width to the hole's depth) of any shape at any angle into metals, ceramics, polymers, and composites regardless of the physical and mechanical properties of the material [31,32]. The industrial use of laser drilling was first investigated by Western Electric in 1985 for drilling of diamond using a ruby laser [33].The schematic of a typical laser drilling process is presented in Figure 1, explaining different phenomena that occur during drilling.

Different types of lasers are used depending on the type of material being drilled (metals, ceramics, polymers etc.), the required hole quality and the associated cost of the laser system being used. From the literature, pulsed CO_2 lasers, Q-switched pulsed Nd:YAG lasers, quasi CW Q-switched fibre lasers, pulsed copper vapour lasers, and excimer lasers have been used for laser drilling [34-39]. The appropriateness of the laser is dependent on the absorptivity of the material being drilled to the laser radiation (wavelength) [32]. The next property that determines the efficiency of a drilling process is the power density/irradiance ($=\frac{P_{avg}}{\pi r^2}$). A higher irradiance can increase the laser drilling speed considering that there is sufficient laser-material interaction.

For a Gaussian laser beam of radius *R* and wavelength λ which is incident on a lens of focal length *f*, the focused laser beam radius is expressed as

$$r = \frac{1}{\pi}\left(\frac{f\,\lambda}{R}\right) \qquad (1)$$

It can also be understood from Equation (1) that the shorter the wavelength of the laser the smaller the focused beam size and hence, irradiance (= $\frac{P_{avg}}{\pi\, r^2}$).

It is well known that the laser intensity decays with depth inside the material of absorption coefficient (α). The relationship is given by Beer–Lambert Law which is

$$\mathrm{I}\ (\mathrm{z}) = I(z) = I_0 e^{-\alpha z} \qquad (2)$$

where, I_0 is the intensity inside the surface after considering reflection losses.

The absorption coefficient (α) is related to the skin depth (δ') as $= \frac{1}{\delta'}$.

Skin depth is defined as the distance within which the laser radiation (photon energy) is absorbed.

Shorter wavelengths are necessary to achieve a smaller theoretical focal point. Similarly, shorter pulse durations are necessary to control the heat affected zone (HAZ) which is very significant when laser-incising wood, as the HAZ alters the internal structure of wood and does not facilitate fluid flow. The size of the HAZ is influenced by the heat diffusion length, l_h, which is the distance over which the thermal energy is conducted during the pulse, and the pulse duration, τ_p,

$$l_h = \sqrt{k\tau_p} \qquad (3)$$

A long pulse, $l_h > \delta'$ leads to significant heating and melting of materials. On the other hand, for short pulse where $l_h < \delta'$, the energy absorbed is highly localized and the material in this region is directly vaporised resulting in a more precise hole shape or cut.

Laser drilling is usually carried out using a pulsed laser with irradiances ranging from 10^6 to 10^{14} W/cm^2 and pulse durations ranging from milliseconds (ms) to femtoseconds (fs) [37,39]. The material under exposure to a laser beam undergoes different phenomena (melting, vaporisation, plasma formation etc.) depending on the laser wavelength used, the laser power density and the laser beam interaction time with the material as shown in Figure 2. The material undergoes melting and vaporisation when in contact with a laser beam with a power density of the order of 10^6 W/cm^2 and a pulse duration in the order of several tenths of a millisecond (ms). The mechanism involved at this power density is energy absorption followed by melting, vaporisation, and expansion of vapour which then creates a strong recoil pressure on the molten material, thereby forming a keyhole by melt ejection. With the power density greater than 10^9 W/cm^2 and the pulse duration in the nanosecond (ns) range (short pulse), the mechanism of laser drilling changes to formation of plasma due to vapour being ionised, increased vapour pressure due to an increase in energy deposition rate over the vaporisation rate, and explosive ejection of molten material outward due to the pressure difference created by the plasma's high temperature and pressure. Further, the mechanism of drilling changes to both non-thermal (Coulomb explosion, spallation and phase explosion) and thermal processes when the laser power density is more than 10^{12} W/cm^2 and the interaction time is in the picosecond (ps) regime (ultra-short pulses).

There are three modes of laser drilling, namely single pulse drilling, percussion drilling, and trepanning, as shown in Figure 3. In single pulse drilling process, a single highly-energetic laser pulse is used. A high pulse energy density with few tens of Joule (J) per pulse energy to tens of mJ per pulse is usually used in this process to achieve the desired depths. Laser pulse duration tends to be kept in the *ms* range to achieve a certain depth as desired by the user. Moreover, both the diameter and depth of the hole can be increased with an increase in the laser pulse energy.

In percussion drilling, several laser pulses of short duration (ns) of similar energy per pulse (mJ) are directed towards the material to be drilled. The depth of hole increases with each laser pulse and as the number of pulses increases the depth of hole increases.

In laser trepanning process, either a pulsed laser, CW, or quasi-CW laser with high repetition rate is used to drill large size holes. This is analogous to a cutting process as a laser is used to cut a shape out of the block by the relative motion of the laser beam along the perimeter of a hole. The laser trepanning process has the advantage of producing larger holes of any size and shape, with improved hole quality [32].

3 LASER-WOOD INTERACTION

Lasers are used for cutting/drilling of metallic and non-metallic materials, including woods, due to their superior performance compared with conventional machining [40,41]. The lasers used are either solid state Nd:YAG or carbon dioxide (CO_2), depending on requirements and process efficiency. That is, the chosen laser is generally dependant on rate and throughput of incisions required, quality required of the incision, cost of the laser system and the overall efficiency of laser wavelength absorbance of the target material. These laser types operate at wavelengths of 1064 nm (Nd:YAG), 532 nm (Nd:YAG), 355 nm (Nd:YAG) and 10.6 μm (CO_2).

At first lasers were only used to cut wood [42]. Initially, it was thought that laser incising was not economically viable [12]. However, with the development of laser technology it has been concluded that lasers could also be applied to laser incision of wood [43-47]. A schematic showing a typical laser incision pattern is presented in Figure 4. The hole pattern and hole density can be varied to maximise the preservative uptake and penetration providing great flexibility to industry for incising and processing different types of wood. The process forms small incisions in the surface of the wood to produce additional preservative intake points. The depths and diameters of these incisions are dependent on the laser processing parameters, including laser energy, focal length, and specific energy of the material [48,49] . However, laser incisions are often associated with the formation of heat affected zones (HAZ), carbonisation and loss of strength [43,47,50]. The formation of the HAZ and carbonisation reportedly can block the fluid flow path by closing the pits [47]. It is to be seen, however, if this is the case for all wood types and for all lasers employed for the laser incision of wood. With this in mind, there is considerably further research needed to determine and verify if lasers do give rise to blocking fluid flow paths.

3.1 Effect of Laser Characteristics on Incising and Uptake

The wavelength of a laser has a strong influence on the machining (including incising) characteristics of woods [51,52]. Several investigations have shown that effective ablation or machining can be achieved in the UV and IR spectral range due to maximum energy absorption (> 80%) by the woods [42]. A range of lasers were studied by Panzner *et al.* [42] to examine the effect of laser type (wavelength) on the ablation rate of woods (pine and beech). An Nd:YAG laser, operating at 1064 nm, showed no sign of ablation below an energy density of 100 J/cm^2. On the other hand, a XeCl excimer laser operating at 308 nm and a CO_2 laser operating at 10.6 μm were both very effective at drilling these wood species. Moreover, the CO_2 laser outperformed the excimer laser, achieving a higher drilling rate due to a 5-fold increase in energy density as shown in Figure 5. This is also highly likely due to the variation in laser-material interaction having an impact upon the coupling of the different energy levels incident on the surface of the woods. The use of high energy density has been shown to improve the machining performance of the wood. However, the use of high energy density during machining of wood also leads to carbonisation of the wood which has been reported to block flow paths reducing wood permeability [47]. This would especially be the case for infra-red (IR) lasers with the laser-material interaction being that of a thermolytical nature rather than direct bond disassociation which occurs with UV lasers. This, thermolytical interaction giving rise to lattice vibrations, along with high energy densities, would give rise to a high temperature gradient that would lead to the observed carbonisation of the wood.

Fukuta *et al.* [51] studied the effect of laser wavelength on the machining performance of heartwood of Japanese cedar, larch, and beech. It was found that the use of longer wavelength and high scan speed resulted in poor, or no machining of the wood. This indicated that there could be an issue in terms of quality control when applying this technology to industry. Having said that, Fukuta *et al.* [53] have recently shown the possibility of employing a polygon scanner to achieve the throughput required for industrial application. With little work evidenced in the literature to verify these claims; however, , more research is needed to ensure that this is the case before industry can consider taking up this technology for laser incision of wood. Even though more research is likely needed, Fukuta et al. [51] showed that through implementing a wavelength of 355 nm (UV), optimum machining was achieved. The absorption of UV light was the reason given [51]. At a wavelength of 355 nm, the heating and evaporation rate were instantaneous which limited the heat transmission to the surrounding wood leading, to ablation only. In the case of 532 nm and 1064 nm wavelengths, heating was slower resulting in heat transmission to the surrounding areas resulting in more carbonisation [51].In another study by Kortsalioudakis *et al*. [50]] a laser energy greater than 70% of the maximum at a fixed wavelength of 532 nm also produced carbonisation. A pulse energy of 301 mJ was preferred in terms of optimised hole geometry and reduced carbonisation. The laser incisions were made to a depth of 4 mm (which was 1/5 of the specimen thickness) using two incision patterns: the distance between holes for the first pattern was 1 × 1 cm, and for the second, 1 × 2 cm. A maximum uptake of 288.6 kg/m^3 was measured for fir wood after laser incision, which was 196% better than un-modified fir. This study investigated uptake of rapeseed oil and CCB preservative. Laser incision of fir and spruce using the same laser incision parameters and liquids for impregnation did not cause any significant loss in bending strength and toughness [54]. Surprisingly, the strength in compression was increased following laser incision although this has not been discussed in detail within the literature and requires further consideration and research. Even though further work is required to fully understand this phenomenon, this would have major positive applications in the industry for treating and preparing those woods for products and applications that involve compressive forces.

The machining of wood can also be enhanced by exploiting the location of the focal point with respect to the piece using a lens, as shown in Figure 6. Placing the focal point at, or just above the surface of the wood improves incising by generating smaller, deeper and more uniform incisions, with reduced carbonisation [49]. Another study produced deeper and smaller diameter holes when the focal point was positioned on the surface of the test piece [51]. The diameter of the hole was found to be 20 µm when the laser focal point was positioned on the surface of the wood. This research highlights how laser systems can be easily and readily manipulated to ensure that the desired incision dimensions can be achieved. It therefote leads one to realise that different incision dimensions, to maximise preservative penetration, for the many different variations of wood can be achieved by simply changing the laser incision processing parameters. The use of a short pulse laser (5 ns) in this study was also shown to minimise the heat affected zone (HAZ). This shows the benefit from using ultrafast lasers for precise incision or micro-drilling. Laser incision of laminated timber was carried out by Ando *et al.* [55,56] to study the impregnation and retention of fire-retardant chemicals. A 1 kW CO_2 laser was used with a pulse duration ranging from 25 ms to 400 ms. The incision density was kept to 1600 holes/m^2 with hole diameters of 1 mm and 1.5 mm. It was found that the laser incision led to a high aspect ratio of hole as compared to mechanical drilling. A significantly higher retention of fire-retardant was observed in laser-incised compared to undrilled timber.

Grad and Mozina [57] used a variety of wood targets (yellow pine, black poplar, silver fir, oak, Tasmanian oak and wood composite) for a laser wood interaction study. A FOTONA Twin light Er:YAG laser, with pulse duration of 160 μs and energy of 0.2 J was used, focussed onto the surface of the wood. The short laser wavelength was chosen because of the increased optical absorption characteristics of the wood, having a specific water content which would give rise to the increased wavelength absorption. The depth of the hole was dependent on the number of laser pulses for holes with depth-to-diameter ratios up to 100 [57]. A decrease in removal rate was observed at aspect ratios above 100. This work showed that there are limitations when applying laser technology to wood processing, especially when requiring high aspect ratios.

3.2 Laser incision pattern and density

Incision density and pattern need to be optimised to maximise uptake without loss of strength. Islam *et al*. [58] studied the effect of laser incision on the preservation of Douglas fir lumber by conventional full cell and passive impregnation methods. A 1.5 kW CO_2 laser was used for laser incision with incision densities of 5,000, 7,500 and 10,000 holes/m^2. There is no information or discussion provided on incision diameters used, a critical point which would have likely had a significant impact on the determination of the optimised incision densities stated. The preservative retention of 482 kg/m^3 was greatest for the incision density of 10,000 holes/m^2. When cross-sectioned, a maximum penetration area of 78 % with fluid was observed with this incision density though this was not significantly different from incision densities of around 7,500 holes/m^2. This study did not report the effects of laser incision density on mechanical properties. Laser incision followed by steam treatment was also reported to improve preservative retention and penetration in the Douglas fir lumber [42]. Although incised against steamed/incised was not compared, the effect of incision density on the absorption and penetration of preservative was and is shown in Figure 7 (a, b). It was found that the increase in incision density from 5,000 holes/m2 to 10,000 holes/m2 increased the absorption from approximately 350 kg/m3 up to almost 500 kg/m3. The penetration area also increased from around 65% at 5,000 holes/m3 to around 80% at 10,000 holes/m3. Even though this work showed that an increase incision density can give rise to an enhanced uptake of preservative, it is not fully conclusive and shows that further work is needed to ensure that a complete understanding can be achieved for the impact of laser incision parameters on the parameters which govern the uptake of liquid preservatives.

3.3 Effect of Wood Density and Moisture Content on Laser Incising

Wood density and moisture content and have been shown to affect laser ablation and incising [43,49,59]. It is widely recognised that timber for aqueous preservative treatments is best treated after drying, to increase uptake of the preservative fluid. Typically bringing the moisture content below 30% is beneficial [18]. The average air-dry moisture content of woods is typically around 20%. Using lasers, a 20% increase in ablation rate was observed when the water content in the wood (beech) was brought down from 30% to 12% as less energy is consumed in drying the wood during the ablation process [43]. The effect of moisture content was thought important to laser cutting of wood as water is highly absorptive to laser radiation (especially to CO_2 laser infra-red radiation) which might reduce laser cutting efficiency [49].

Denser woods are more difficult to ablate or incise [59]. Figure 5a shows ablation to be greater in lower density springwood than latewood (summerwood) of pine. A lower wavelength laser was shown to give improved incising in dense wood [57]. The carbonisation effect was also found to be higher in denser woods [59]. It is important to note that since density of some species varies with anatomy, that depth of and rate of incision will not only relate to wood species but the orientation of growth rings to the surface of the piece being incised. This is something not often considered in studies. Having said this, it is important density variation between and within species/pieces be considered as this will significantly impact upon aspects such as laser-material interaction, throughput times and incision hole quality/dimensions.

3.4 Effect of Laser Incising on the Structure of Wood

Laser interaction with wood results in structural change in wood near to the laser processed area because of thermal processes. The area affected is termed the heat affected zone (HAZ) as shown in Figure 8. Carbonisation of the HAZ has been observed at lower laser energy densities [43]. Carbonisation and alteration of the cellular structure has led to a decrease in length of liquid uptake because of modification of structure in HAZ [47]. The high laser intensity (~10^7 W/cm^2) employed during laser cutting of wood makes this a thermal process which results in change of wood structure at the surface of the heat affected zone (HAZ) and modification of wood polymers (e.g. lignin and cellulose) [60]. Therefore, although holes produced by laser incising provide more liquid-intake points, and the amount of liquid uptake increases with increasing hole diameter, the condition of the heat affected zone appears to influence uptake and should therefore be considered in any future studies. The use of higher energy densities, higher moisture content wood and inert gas (e.g. N_2) around the point of incision have been found to suppress the detrimental carbonisation [43,52,60].

Table 3 summarises findings from studies examining laser-incising of different wood species. Most studies used longer wavelengths as it is well known and accepted that these longer wavelengths are capable of more rapid incising. With longer wavelengths (e.g. 10.6 μm), higher pulse energies (5J-228J) and longer pulse durations (10 ms-190 ms) holes between 20- 70 mm deep could be produced [46-48]. The use of a wavelength of 10.6 μm was beneficial since it increased the drilling rate 20-fold with only a 5-fold increase in energy compared with other competing laser technologies such as Nd:YAG lasers [42]. Kortsalioudakis *et al*. [50] reported 532 nm as the preferred wavelength for laser incision in their studies, with uptake of the preservative increased by 196%, where the drilling depth was 4 mm and hole diameter w 1 mm. Cleaner and higher aspect ratio holes can be drilled with Q-switched Nd:YLF solid-state laser (λ= 349 nm) and Q-switched Nd:YVO4 solid-state laser (λ= 355 nm) with a pulse duration of 5 ns. These incised holes were found with little or no carbonisation which is believed to be beneficial for preservative treatment although this study did not investigate whether this was the case [51]. It should also be noted that some of the works conducted have reported the impact of laser incision density on the uptake of preservative liquids. Generally, an increase in laser incision density increased the penetration and absorption of the liquid preservatives [11,28,45].

4 OUTLOOK FOR LASER INCISING OF WOODS

Considering that there are few manuscripts within the literature which fully investigate laser incising of wood and that there is an increase in demand for wood products (owed to requirements of worldwide sustainability), there is a significant demand for the development of techniques for the incision of woods to promote and enhance the penetration and uptake of resin preservatives. Because of this, work is needed on these incision techniques to ensure that they are optimised for the numerous wood types and resin preservative treatment applications. In addition to this, work is required on each of the processes to ensure industrial requirements in terms of quality and throughput are achieved. Fukuta *et al.* [53] has employed a polygon scanner with a UV 355nm laser to achieve relatively high-speed processing in the attempt to achieve industrial throughput rates with incisions with sufficient quality. Having said that, whilst woods may have sufficient absorption characteristics for UV laser technology, it would be of significant interest to compare the different laser types, especially comparing UV and CO_2 lasers. With minimal work having been carried out in the field, this work is needed to conduct a thorough investigation of the different laser types for wood incision in order to ascertain the optimum laser system to provide wood incising for industry.

Another aspect which needs to be considered and researched further is that some have reported that the process of laser incision gives rise to the blocking of pores and natural flow channels within the wood [47]. Similar to the high-speed processing work by Fukuta *et al.* [53], there is little further evidence or discussion within the literature to confirm this. In fact, some works [13,14] have shown that CO_2 laser incisions can give rise to the enhanced uptake of resin following laser incision. This would highlight that laser incision does not always block the natural flow paths within the wood. Having said that, more research is needed to identify if this is true and if it is dependent on the type of laser used and/or if it is dependent on the wood type implemented.

5 SUMMARY

In this review paper, studies on laser incision of wood, and associated physical phenomena and mechanisms involved in laser wood interactions have been reported. Best practices for carrying out laser incision of wood in terms of laser type (wavelength) and process parameters have also been discussed and considered, in addition to discussion surrounding the scope of potential future work in the field.

Most of the early research on the laser incision of woods used CO_2 lasers (10600 nm) due to their fast processing characteristics. The faster processing nature of the CO_2 laser results from the maximum absorption of laser radiation by the wood structure and its ability to deliver higher power density. Increased hole depth occurred with increased laser power and pulse duration. Moreover, preservative impregnation and retention were found to improve following laser incision of woods using CO_2 lasers. Preservative intake was found to increase with increased incision density as it increases the number of preservative intake points. However, CO_2 laser incision of woods tended to resul in carbonisation and structural damage due to heat affected zone (HAZ) formation. It was found that preservative treatment was negatively affected structural changes to wood due to formation of the HAZ and carbonisation.

To overcome the structural changes caused by CO_2 lasers, short-wavelength (UV) and short-pulse (ns) lasers have been trialled. Short-wavelength lasers enable small focal point diameters and hence, higher energy densities. Shorter pulse durations reduce HAZ and carbonisation. Most recent studies have been conducted with wavelength in the UV range (305-355 nm) where the absorption of laser radiation by the wood is ~ 80%. The pulse durations have been kept short (*ns)* to limit the heat damage to the surrounding wood. However, none of the studies showed a process that is free from HAZ and/or carbonisation. The major disadvantage of UV laser incising is the long processing times required, which is an obstacle for the timber industries adopting the process. Nonetheless, incision rates can be increased by positioning the focal point below the surface, using higher energy density and using woods of lower moisture content. To the Authors' knowledge, to date,no work has been conducted and reported to investigate the effects of UV laser incising on impregnation and retention of preservatives. Efforts should also be given to increase the UV laser incision rate by optimising the laser processing parameters and choosing optimised optics.

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Table 1: Classification of wood species based on their level of impregnability.

Ease of Treatment	Wood zone	
Level	**Sapwood**	**Heartwood**
Easy	Acacia, alder, beech, maple, oak, poplar, walnut	
Medium	Ash, fir, chestnut, larch	Ash
Difficult	Spruce, teak	Poplar, walnut
Extremely difficult		Acacia, oak, chestnut, larch, teak, beech

Table 2: A comparison of retention and penetration in un-incised and drilled fir wood [24].

Pre-treatment	Retention kg/m^3	Relative impregnated area (%)
Un-incised	4.80	100
Drilled perforation (Mechanically incised)	9.29	193.54

Table 3: Summary of literature relating to laser incision of woods

Wood type	Laser type (Wavelength)	Laser pulse energy (E)/ Output power(P)	Pulse duration	Hole dimension	Hole pattern and density	Findings
Pine and Beech	Nd:YAG laser (1064 nm); XeCl Excimer laser (308 nm); CO2-TEA laser (10600 nm)	E= 1.8 J (Nd:YAG laser)	8 ns (1064 nm), 40 ns (308 nm), 1.2 µs (10.6 µm)	NA*	NA*	Changing the wavelength of the light from 308 nm to 10.6 µm with 5-fold increase in energy density increased 20-fold increase in ablation rate.
White oak, Northern red oak, yellow poplar, sand loblolly pine	CO2 laser (10600 nm)	P = 75 - 115 W	0.2 - 0.4 s	Diameter = 5 mm; Depth = 8.89 -27.94 mm;	Hole density= 4 holes/in^2, 36 holes/in^2, and 98 holes/in^2.	Laser incision led to decrease in modulus of rupture up to 46%. A hole density of 98 holes/in^2 also showed significant reduction in bending strength. A significant reduction in lumber drying times was observed following laser incision.
Douglas fir lumber	CO2 laser (10600 nm)	P= 1500 W	NA*	NA*	Hole density= 5,000, 7,500 and 10,000 holes/m^2	Maximum preservative retention (482 Kg/m^3) was observed for 10000 holes/m^2;
Hinoki, Sugi, Karamatsu, Douglas-fir	CO2 laser (10600 nm)	E= 30 - 228 J	25 - 190 ms	Diameter= NA*; Depth = 30-70 mm.	Hole position= 25 mm (X) × 6 mm (Y) and 10 mm (X) × 4 mm (Y)	Maximum dye retention of 317 Kg/m^3 in Sugi with 70 mm hole depth. Maximum length and width of dye penetration away from incision was also observed for Sugi.
Yellow cedar, Chinese fir, poplar (heartwoods)	CO2 laser (10600 nm)	P= 1000 kW	50 - 300 ms	Diameter = 0.70 mm to 1.32 mm; Depth= NA*	Hole position= 30 mm (X) × 30 mm (Y)	Increased preservative uptake with increase in hole diameter. Changes in wood structure in HAZ following laser incision.
Sugi, Karamatsu, Igem, Mizunara, White serya, Kiri	CO2 laser (10600 nm)	P = 300 - 1600 W and; E= 0.1-5 J	0.2 - 10 ms	Depth = 3-22 mm. Diameter = 0.7-1 mm	3 holes with 3 mm spacing	Specific gravity (density) of the wood affects the depth of holes. Increase in focal length increases the depth and diameter of holes. Increase in the laser irradiated energy increases the depth of holes.
Fir and spruce (Sapwood)	Q-switched Nd: YAG (1064 nm, 532 nm, 355 nm)	E= 301 and 800 mJ	4 ns	Depth=4 mm, Diameter=1 mm	Hole position= 10 mm (X) × 10 mm (Y) and 10 mm (X) × 20 mm (Y)	Optimised laser wavelength= 532 nm; Increased impregnability (196%); Increased compression strength; No difference was observed for two different drilling patterns
Sugi (Black heart)	CO2 laser (10600 nm)	P = 1700 W	1.1-1.3 s	Diameter= NA*; Depth= NA*	Pattern= 50 mm × 8 mm, 33.2 mm × 6 mm, and 30.4 mm × 4.4 mm. Incision density= 10000,	Drying times were reduced by 7-8% for low incision densities and 16-43% for high incision densities.

					20000, and 30000 holes/m^2	
Japanese Cedar, Japanese larch, and beech (Heartwood)	Q-switched Nd:YLF solid-state laser (349 nm) and Q-switched Nd:YVO4 solid-state laser (355 nm)	P= 0.08 and 5 W; E= 80 and 100 μJ	5 ns and 12 ns	Diameter= 20 μm, Depth= 5 mm.	Hole position= 0.5 mm (X) × 0.3 mm (Y), Hole density= 6670 holes/m2	No change in diameter through depth was observed. Carbonisation not observed. Maximum depth (5 mm) and no visible HAZ was observed for keeping laser focal point at the surface of the wood. Hole depth was shallower for high-density beech. High-aspect-ratio holes of diameter 20 μm and depth 5 mm within several seconds at a power output of 80 mW.
Japanese Cedar	CO2 laser (10600 nm)	P= 1000 W	0.1 s	Diameter=1–1.5 mm; Depth= NA*	Hole position= 78 mm (X) × 8 mm (Y); Hole density= 1600 holes/m2	High aspect ratio of holes can be obtained by laser incision over mechanical drilling. Higher retention of fire-retardant chemicals in drilled timbers as compared to undrilled timber; No significant difference in retention of fire retardant chemicals between laser incised timbers and mechanically drilled timber.
Red spruce (Heartwood)	CO2 laser (10600 nm)	P = 25-100 W	150-600 ms	Diameter= NA*; Depth= 10-30 mm	Along the grain= 20 and 15 mm and across the grain= 2 mm. Hole density= 248 holes/m^2 and 328 holes/m^2.	Deeper holes were observed for higher pulse durations. Longitudinal penetration was maximum with higher power and higher pulse duration. Penetration of preservative was around 1- 5 mm below the incision. Radial penetration was around 1-2 mm from incision. No significant loss in strength was observed following laser incision. Higher incision density led to higher preservative retention. Increased preservative penetration was observed for laser incised woods than control specimens.
Black spruce and Douglas-fir	CO2 laser (10600 nm)	P = 125-500 W	0.03-0.5 s	Diameter= NA*; Depth= 10-42 mm	Longitudinal spacing= 18-72 mm.	Increased incision density increased the preservative penetration and retention.

*NA: Not available to report

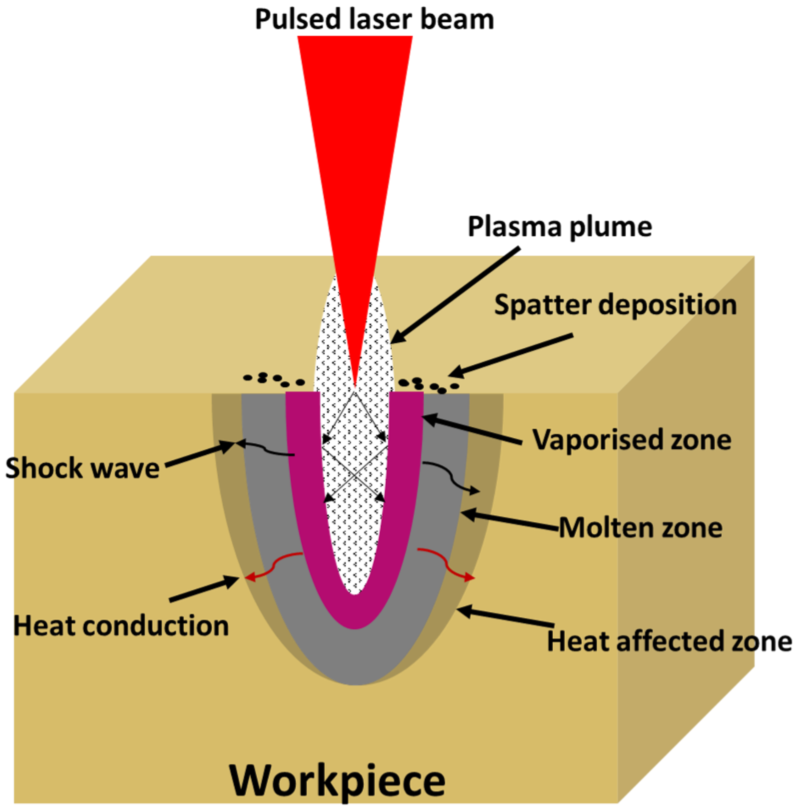

Figure 1: Schematic representation of laser drilling process.

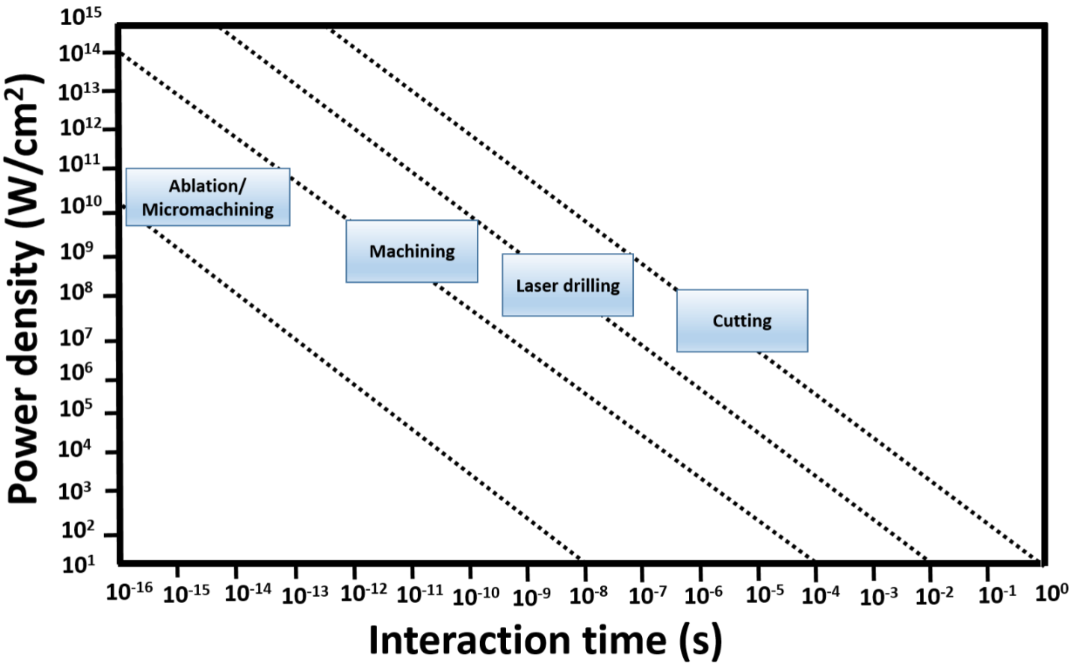

Figure 2: Power densities and interaction times in different laser material processing events.

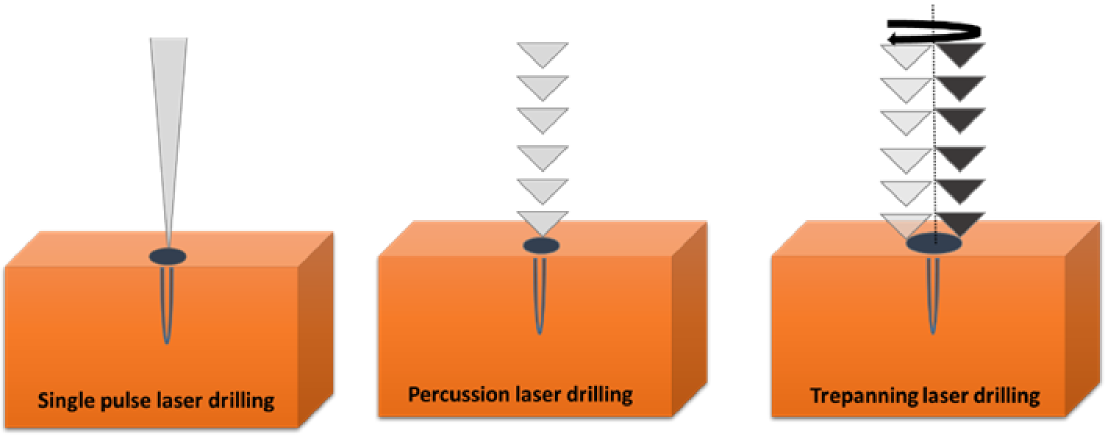

Figure 3: Modes of laser drilling.

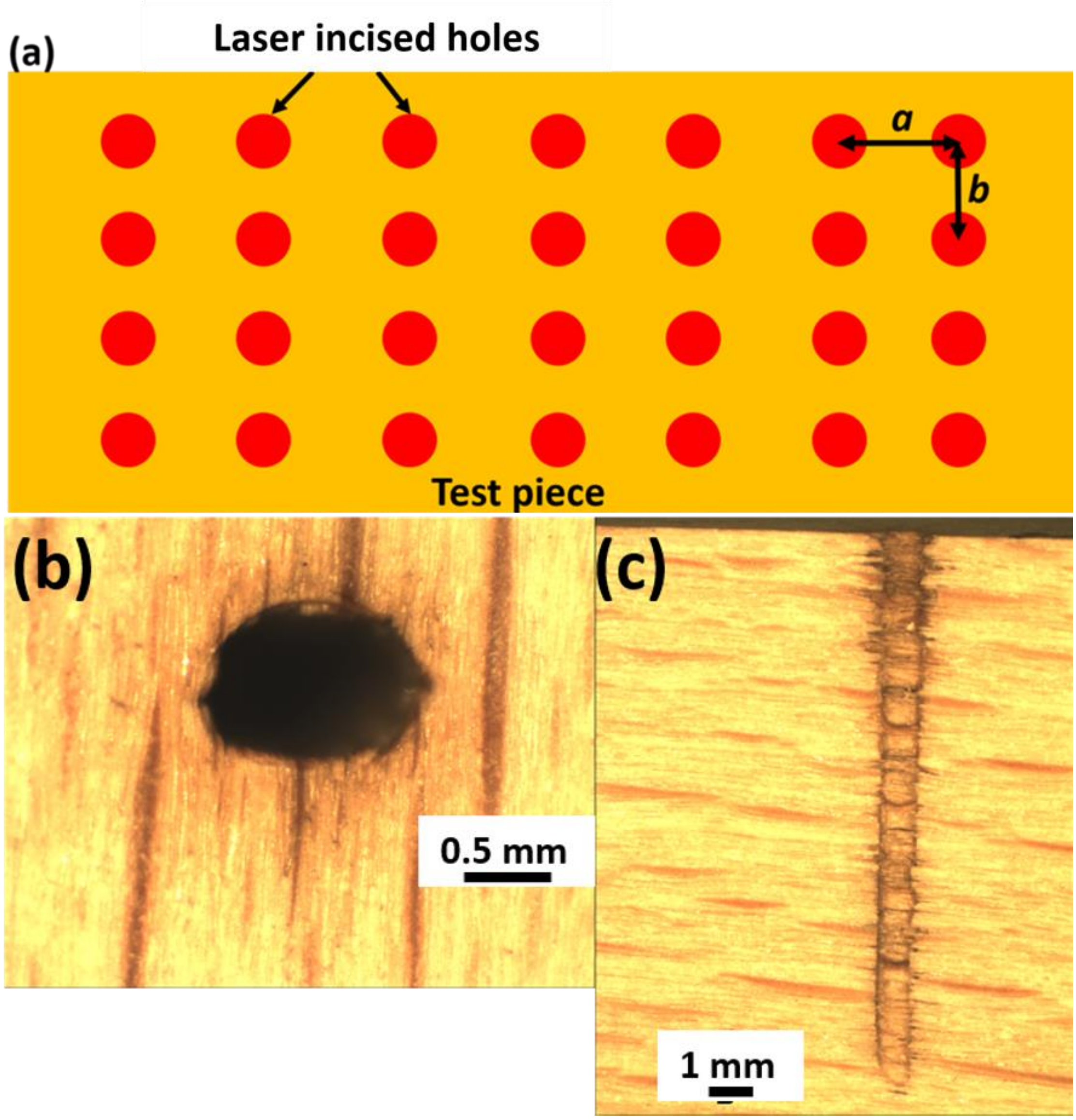

Figure 4: (a) Schematic representation of laser incised holes on the face of a test specimen, (b) Laser incised hole in tangential face of block, and (c) cross-section through laser incision in tangential direction. (Wood species: European beech).

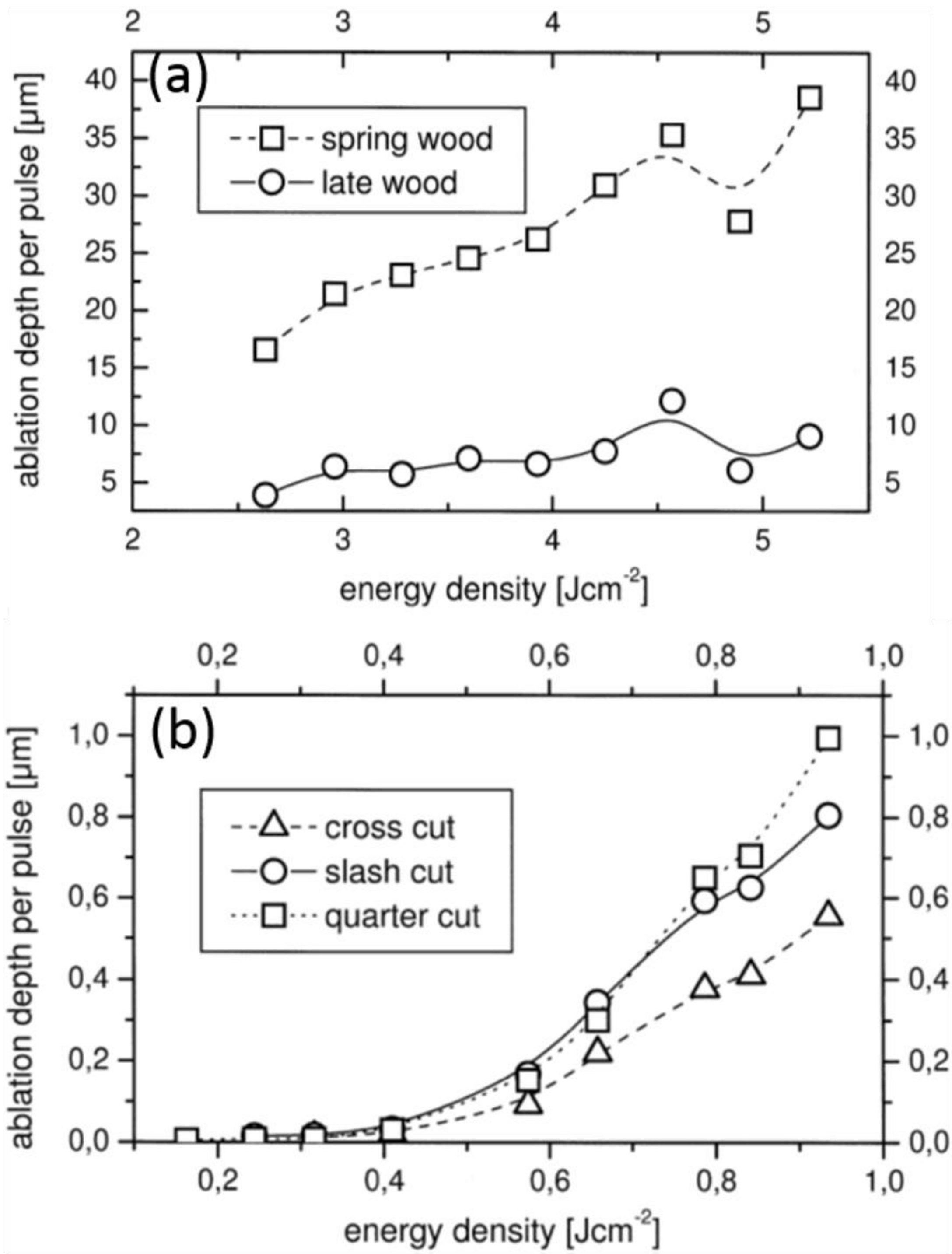

Figure 5: Effect of laser energy density on the ablation rate. (a) CO2-TEA laser incised pine, cross cut, water content 10%. (b) XeCl excimer laser incised beech average of spring and late wood, water content 10%.

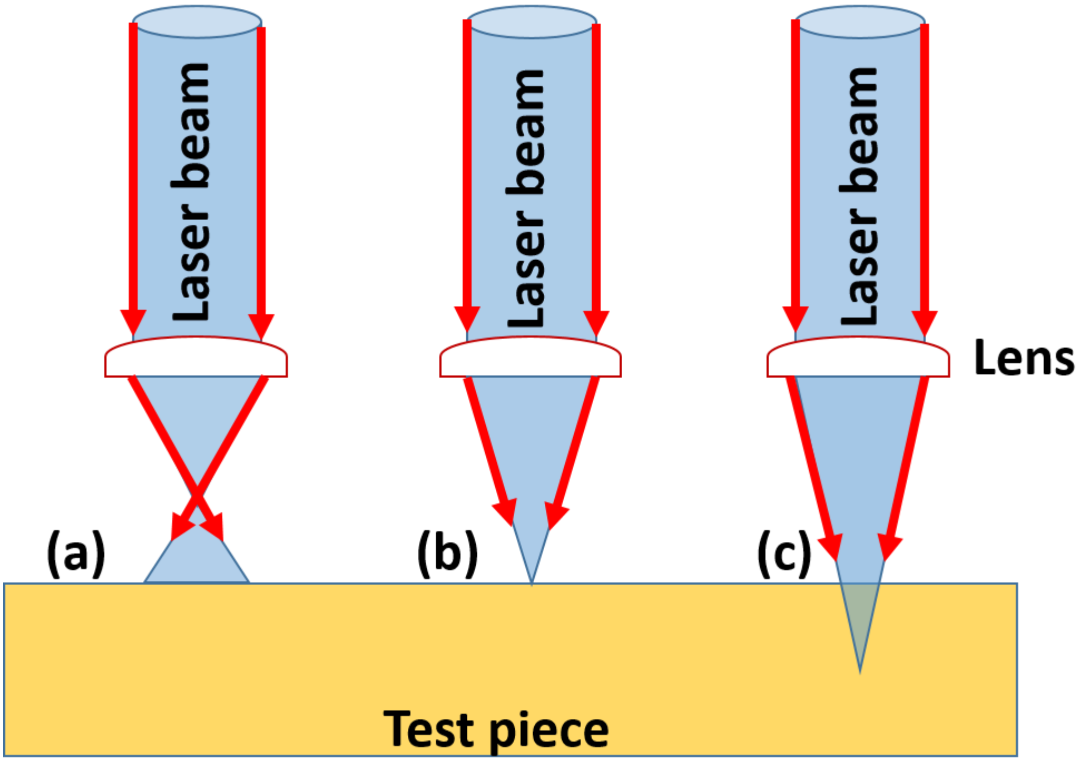

Figure 6: Positioning of focal point with respect to the test piece. (a) above test piece, (b) on the surface of the test piece, and (c) at or just above the centre of the test piece.

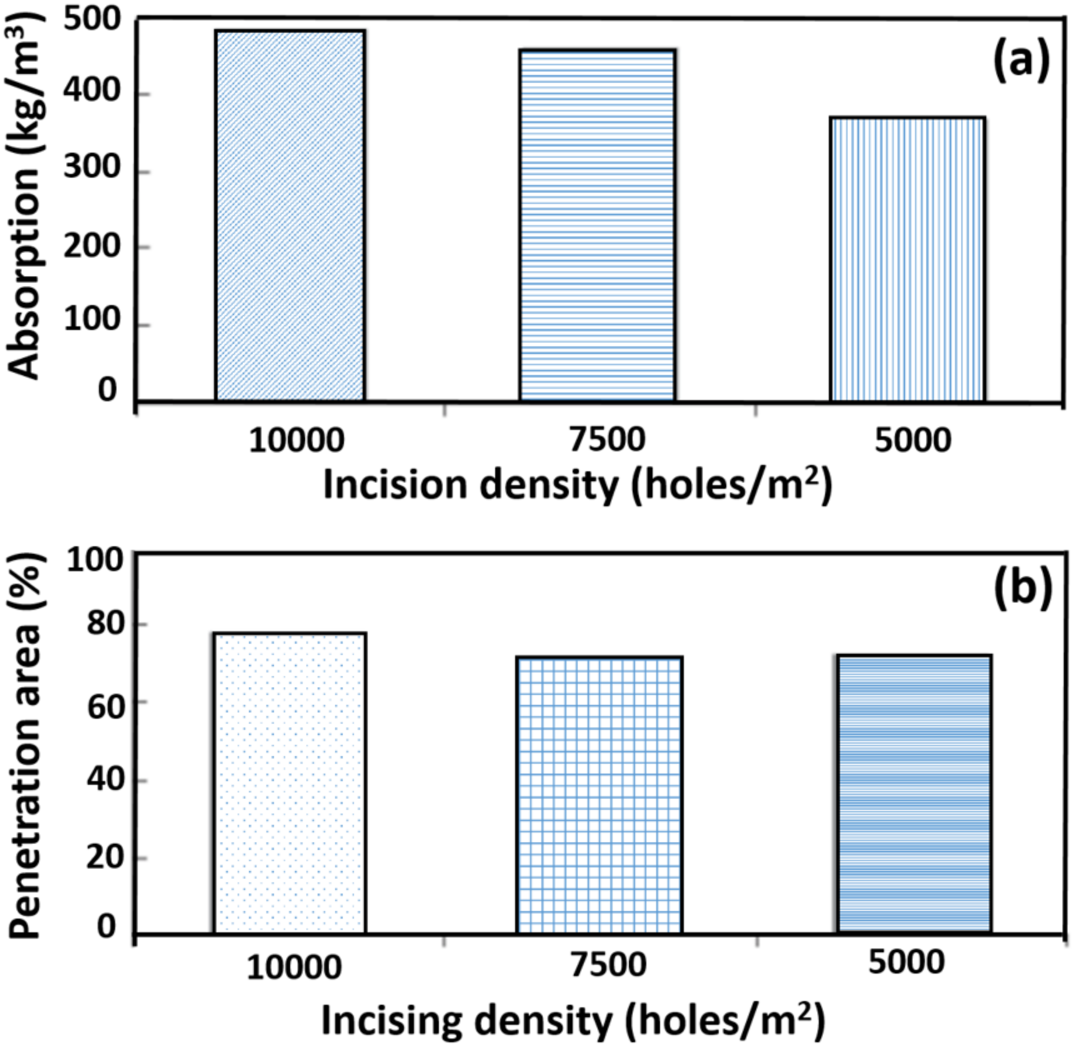

Figure 7: (a) Preservative absorption and (b) preservative penetration for different hole densities incised by laser in Douglas fir lumber [42]

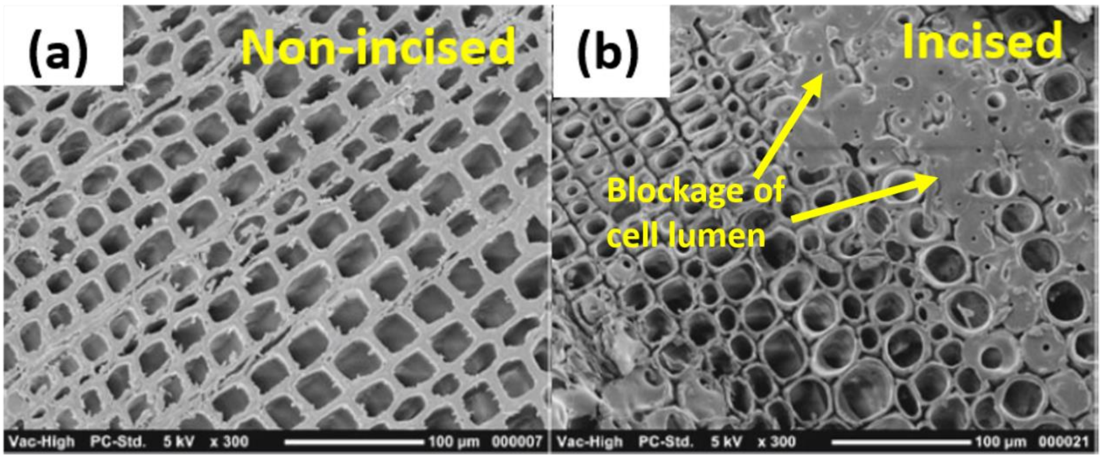

Figure 8: Scanning electron micrographs of cross-section of Chinese fir showing (a) non-incised sample and (b) heat-affected zone of an incised sample laser incised with an applied laser power of 1 kW and a pulse duration of 300 ms.